Conceptualization and Application of Arctic Tundra Landscape Evolution Using the Alaska Thermokarst Model

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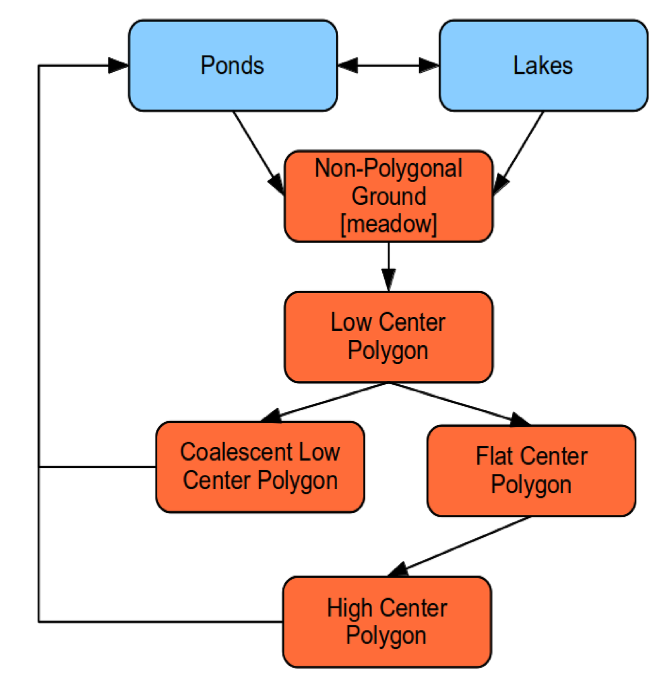
I. INTRODUCTION

Thermokarst topography forms whenever ice-rich permafrost thaws and the ground subsides due to the volume loss when excess ice transitions to water. The Alaska Thermokarst Model (ATM) is a large-scale, state-and-transition model designed to simulate transitions between [non-]thermokarst landscape units, or cohorts. The ATM uses a frame-based methodology to track transitions and proportion of cohorts within a 1-km^2 grid cell. In the arctic tundra environment, the ATM tracks thermokarst related transitions between wetland tundra, graminoid tundra, shrub tundra, and thermokarst lakes. The transition from one cohort to another due to thermokarst processes can take place if seasonal thaw of the ground reaches ice-rich soil layers either due to pulse disturbance events such as a large precipitation event, wildfire, or due to gradual active layer deepening that eventually reaches ice-rich soil. The protective layer is the distance between the ground surface and ice-rich soil. The protective layer buffers the ice-rich soils from energy processes that take place at the ground surface and is critical to determining how susceptible an area is to thermokarst degradation. The rate of terrain transition in our model is determined by the soil ice-content, the drainage efficiency (or ability of the landscape to store or transport water), and the probability of thermokarst initiation. Tundra types are allowed to transition from one type to another (i.e. a wetland tundra to a graminoid tundra) under favorable climatic conditions. In this study, we present our conceptualization and initial simulation results of the ATM for an 1792 km^2 area on the Barrow Peninsula, Alaska. The area selected for simulation is located in a polygonal tundra landscape under varying degrees of thermokarst degradation. The goal of this modeling study is to simulate landscape evolution in response to thermokarst disturbance as a result of climate change.

III. LANDSCAPE TRANSITIONS



Terrestrial Cohorts:

- 1-directional transitions
- Coalescent Low Center Polygon and High Center Polygon cohorts transition to the Pond cohort
- Transition between cohorts occurs when the active layer depth penetrates the protective layer (Figure 4)
- Rate of transition is a function of the ground ice content, the drainage efficiency (landscape ability to store or transmit water, and the degree of active layer penetration into the protective layer)

Pond and Lake Cohorts:

- Permafrost thickness does not allow vertical lake drainage (through the bottom of the permafrost)
- Lakes and Ponds expand vertically and laterally at a prescribed rate
- The difference between lakes and ponds is based upon the presence or absence of liquid water throughout the year (i.e. in deep lakes the lice thickness is less than the lake depth)
- Lateral pond/lake drainage results in the transition from the lake/pond cohort to the Wetland Non-Polygonal Ground cohort (exclusively)

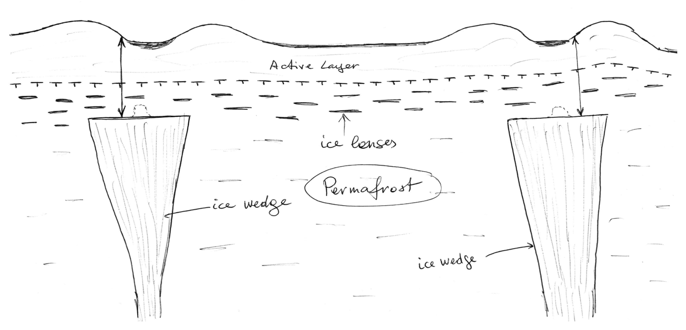


Figure 4. Protective layer illustration. The protective layer is the land surface and the top of ice-rich soils (or massive ice bodies). The protective layer acts as a buffer between surface processes and underlying permafrost.

IV. MODEL TEST/STUDY AREA

The Barrow Peninsula is the test region for evaluating the dynamics of the tundra thermokarst transitions. The Barrow Peninsula is located in a polygonal tundra landscape under varying degrees of thermokarst degradation. This area was selected for model evaluation in order to take advantage of the ongoing observations and modeling studies of the DOE NGEE-Arctic project. Much of the evaluation of the ATM dynamics will be to compare the simulated expansion rates of thermokarst landscape units to what has been observed.

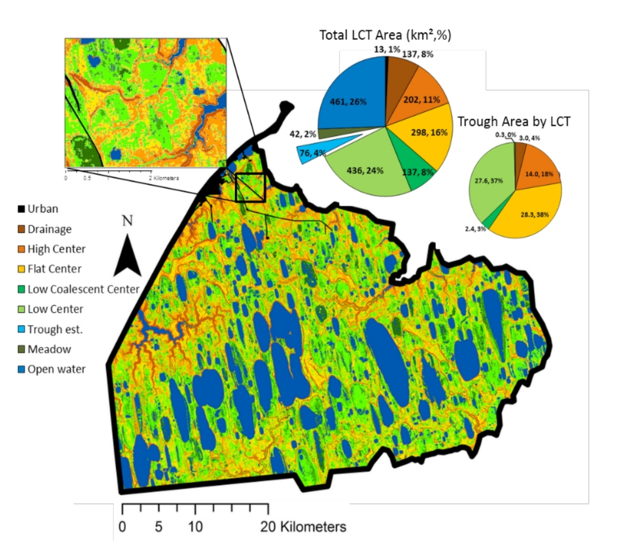


Figure 5. Study area/Model Domain. The Barrow Peninsula (1972 km^2) is being used to develop transition rates for all the Wetland Tundra cohorts, lakes and ponds. Initial cohort distribution is based upon the work of Lara et al (2014).

II. MODEL DESCRIPTION

The ATM is a state-and-transition model designed to simulate transitions among landscapes caused by thermokarst disturbance. The ATM uses a frame-based methodology to track transitions among landscape units (cohorts) with a 1 km^2 grid cell. Although the ATM does not track cohorts in a spatially explicit fashion, initial information on the proportion of each grid cell is required. The frame logic uses a logical rule set to determine the probability that a cohort will remain in its current landscape unit (parent cohort) and the probability that it will transition to another landscape unit (child cohort) (Figure 3). The probability of initiation and the rate of transition is a deterministic model. The logical rule set considers factors such as climate, topography, fire, land use, hydrology, soil texture and ice content.

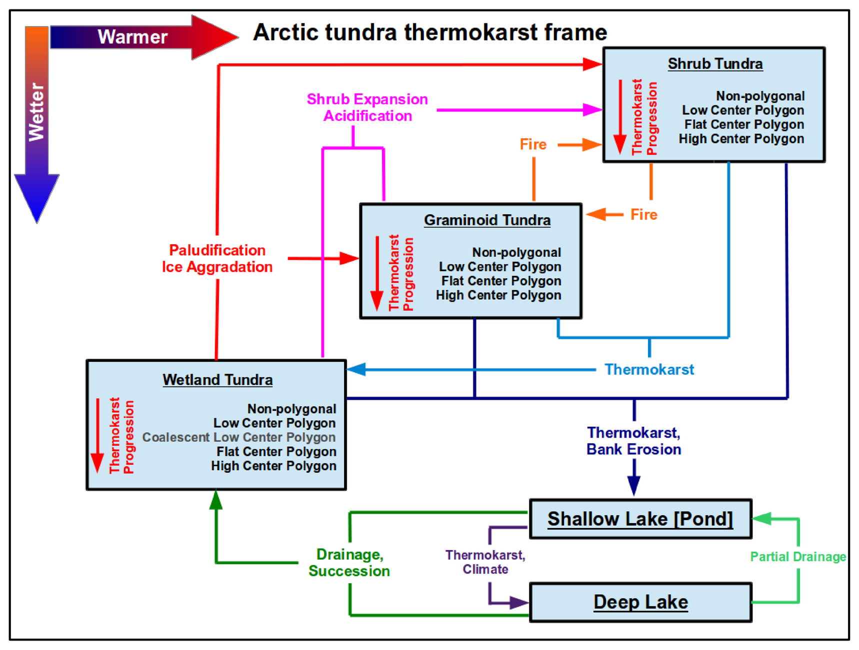


Figure 1. Description of frames and trajectories. The arctic tundra component of the ATM considers thermokarst related transitions between the following eco-types: wetland tundra, graminoid tundra, shrub tundra, and lakes. Within each terrestrial eco-type, the landscape type defines the state of thermokarst degradation, which is assumed to coincide with the degradation of an ice-wedge polygon.

Figure 2. Examples of landscape types simulated in the ATM.

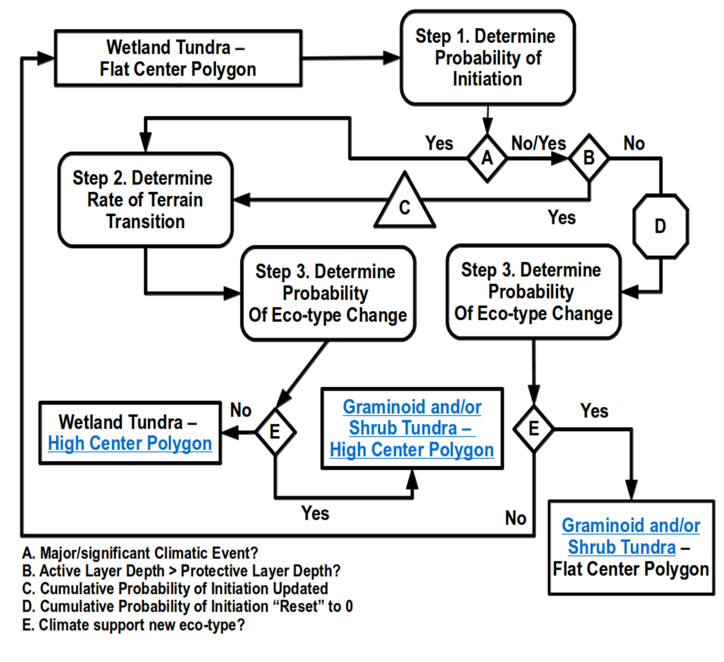
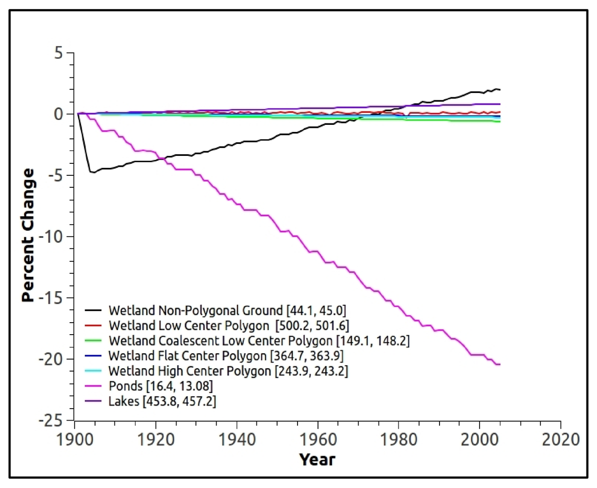


Figure 3. Example of a frame. Frames contain the logic and needed to determine the fate of each cohort present in the simulation domain. At this point in time, the ATM is tracking 15 different cohorts – 13 terrestrial and 2 lake. A unique frame, or decision tree, exists for each cohort.

V. INITIAL RESULTS



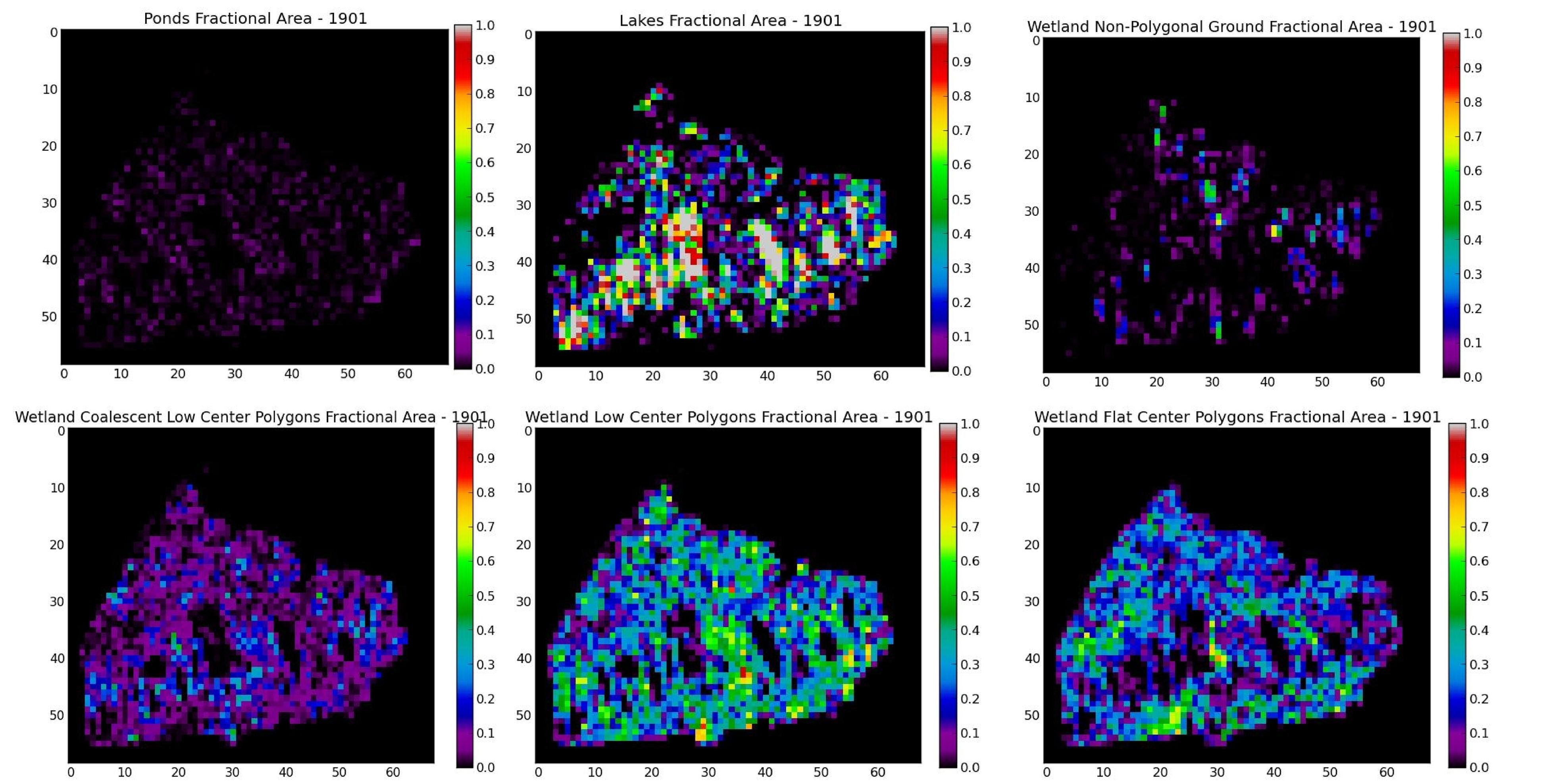
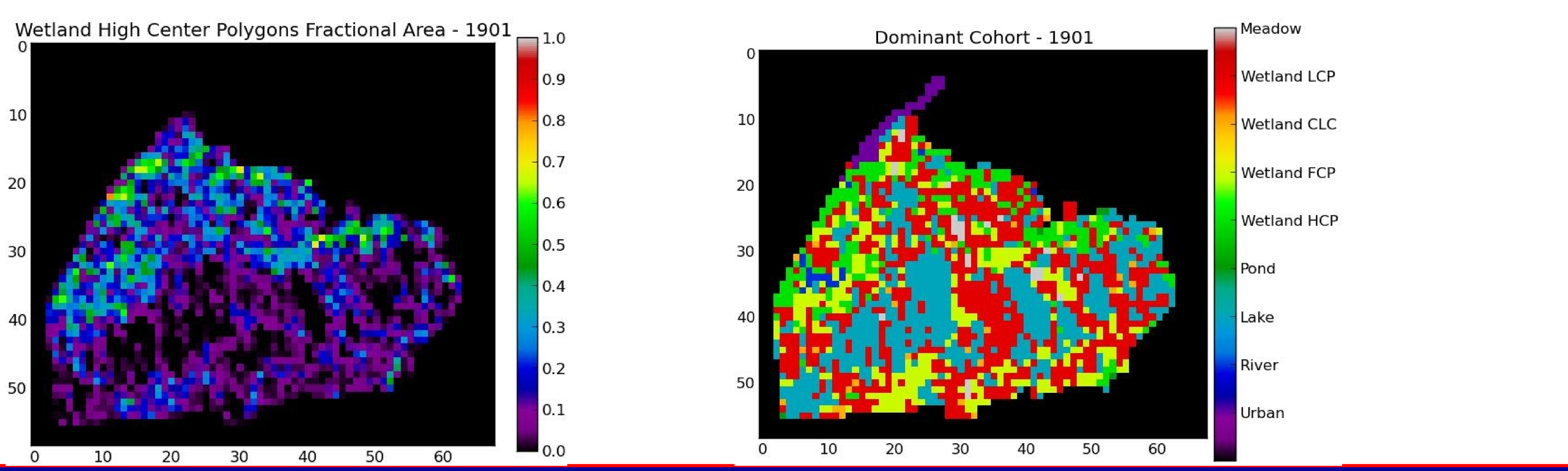
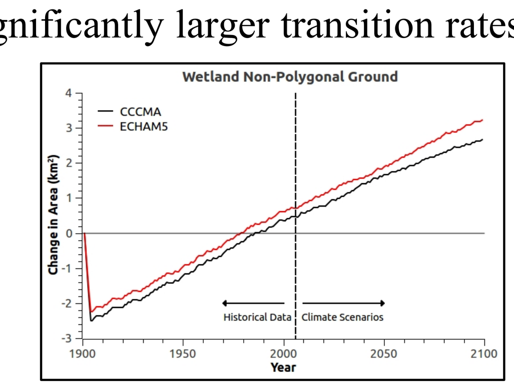


Figure 6. Initial Simulation Results. Results presented here are from the model calibration process. **(A)** Percent change in total cohort area. Values in brackets indicate the cohort area at the beginning and end of the simulation. **(B)** Fractional areas of each cohort. The sum of all cohorts in a single model element sums to 1.0. **(C)** The dominant cohort (largest fractional area) for the model domain.



VI. DISCUSSION AND FUTURE WORK:

- Continue function development/parameterization to describe probability of initiation and transition rates from observation and fine-scale numerical experiments.
- Add additional cohort layer to specify Young or Old Drained Thaw Lake Basins. Terrestrial cohorts located in Young DTLBs have a significantly larger transition rates compared to those in Old DTLBs.
- Incorporate eco-type transitions
- Robust sensitivity analysis
- Conduct scenario simulations in order to predict future landscape evolution



VII. ACKNOWLEDGEMENTS

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